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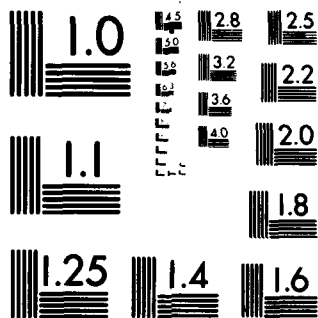
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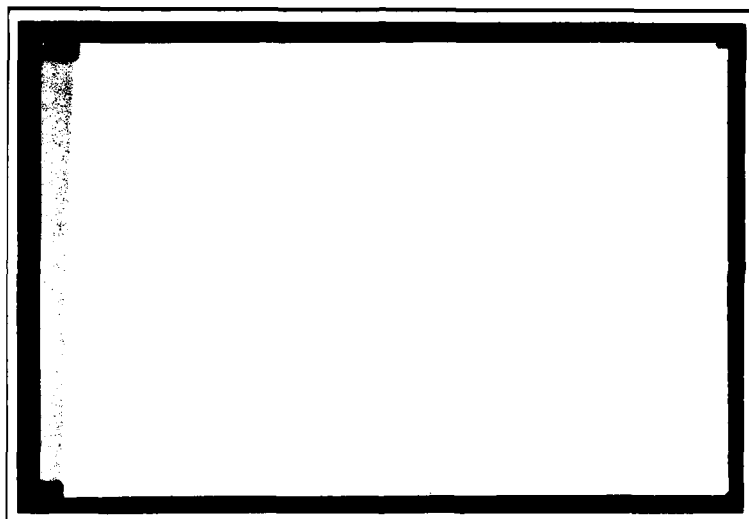
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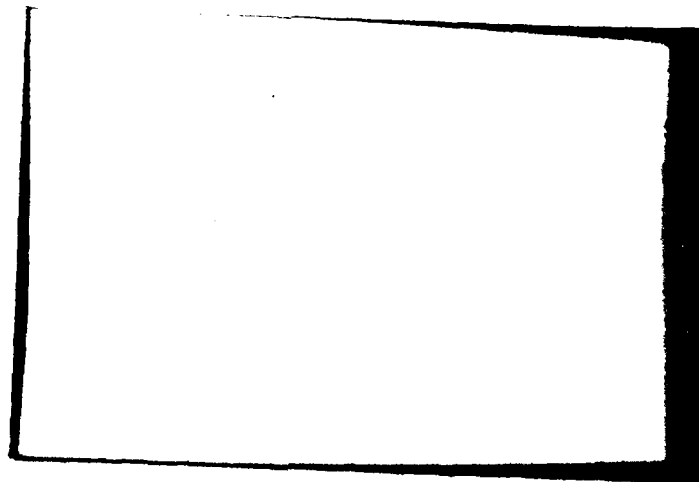
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COOPERATIVE INVESTIGATION OF THE NOISE  
PRODUCING REGION OF AN AXISYMMETRIC JET

by

(10)

W.K./George, R.E.A./Arndt ~~and~~ H.M./Nagib

(9)

FINAL REPORT

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July 1980

State University of New York at Buffalo  
Buffalo, New York 14214

\*Work continues through new contract with  
IIT. This interim "final report" is  
necessitated by the transfer of program  
administration from SUNY.

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## Abstract

The objectives of this three-university effort are: to determine whether or not large scale structures exist in the mixing layer of an axisymmetric jet; to determine whether or not these large scale structures (if they exist) contribute to the radiated noise; and to quantify the above conclusions so that the results can be used for evaluation of jet noise theories and for prediction of radiated noise. This is a report on the initial phase of the work in which the primary emphasis has been on the construction of the experimental facilities, the acquisition and assembly of the measurement hardware and the development of computer software. Noteworthy advances include an analysis and extension of the burst-mode LDA, and the continued development of digitally sampled flow visualization techniques.

Experiments on various nozzle shapes at low Reynolds number indicate that nozzle shape plays an important role in determining the vortex pairing in the mixing layer and the radiated noise. This does not appear to be the case at high Reynolds numbers. The preliminary conclusion is that the pairing and turbulence structures observed at low Reynolds numbers have little to do with jet noise.

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## BACKGROUND

The objectives of this three-university effort have been:

1. To determine whether or not large scale structures exist in the mixing layer of an axisymmetric jet.
2. To determine whether or not these large scale structures (if they exist) contribute to the radiated noise.
3. To quantify the above conclusions so that the results can be used for evaluation of jet noise theories and for prediction of radiated noise.

The investigation is being carried out in three parts. At SUNY/Buffalo a detailed study of the turbulent velocity field is being carried out using laser Doppler and hot-wire anemometry techniques in a unique computer-controlled experiment. The 400,000,000 cross-spectra obtained will be analyzed with Lumley's orthogonal decomposition technique to obtain a deterministic and objective picture of the three-dimensional growth and decay of the large scale structures. At the University of Minnesota, a detailed study of the radiated noise field in a similar facility is being carried out. The results of this investigation will be analyzed with a decomposition similar to that used by Michalke to determine the coherent contributions to the radiated noise field. The quantitative data obtained in these two experiments will be used in conjunction with Lighthill's equation to determine whether and how the large scale structure in the jet mixing layer contributes to the observed radiated noise. At IIT, detailed and quantitative flow visualization experiments are being carried out. These experiments will not only assist in interpretation of the results of the decomposition experiments, but also provide a direct means of evaluating the effect of extraneous influences on the jet structure development.

An advisory panel of leading turbulence and aeroacoustic scientists from the university and industrial communities meets on a regular basis with the principal investigators and the AFOSR monitors. Not only does this provide a greater perspective than would be possible at a single university (or even the three universities) - but it also provides a direct opportunity to interact with a broader range of research investigators on jet structure and noise.



### PROGRESS AND ACCOMPLISHMENTS

During the initial funding period (4-1-78 to 3-31-80) the primary emphasis has been on the design and construction of the experimental facilities, the acquisition and assembly of the measurement hardware, and the development of the mini-computer software. The hardware and software development has been particularly time consuming at all three institutions because in all three cases the demands of this investigation have required extending substantially both our own expertise and the state-of-the-art of computer related flow measurements. At this juncture, all components are operational in the three facilities. Appendices I, II and III describe in moderate detail the facilities at SUNY/Buffalo, IIT, and Minnesota. Several specific problems and technical advances are detailed below.

#### A Problem with the Contraction

Primary to our efforts to insure commonality of the three facilities is the selection of a common contraction which minimizes the flow sensitivity to extraneous and facility dependent disturbances, thereby insuring that all three centers are measuring the same phenomenon. The contraction shape, flatness of the exit velocity profile and initial mixing layer development have proven not to be sufficient criteria to insure that the mixing layers in the three facilities are similar. Consequently, an experimental program was carried out at IIT to determine the sensitivity of the mixing layer development to contraction design and environment, prior to constructing the "final, common" contraction.

At the April 1979 meeting of the principals at IIT, a contraction based on a 5th order polynomial was selected as having the best overall properties (minimum overshoot and turbulence intensity; The background turbulence level of 0.13% was about a factor of 2 to 3 lower than that reported elsewhere or thought possible.) Testing since April 1979, however, has indicated that unlike

the other contractions tested, which are similar to those used by other investigators, the 5th-order polynomial nozzle does not give rise to the expected pairing activity in the mixing layer over the similar operating conditions. The fact that this by all measures is a superior contraction raises a serious question about whether pairing is or is not an intrinsic mixing layer mechanism. These measurements also confirmed that the exit turbulence intensity can be controlled to a level as low as 0.05%.

Clearly this question must be resolved before the final choice of contraction is made since if pairing is an appropriate test, then the 5th order polynomial is bad; whereas if pairing is the extraneous phenomenon or one which depends on the operating conditions, then more care must be exercised in selecting a nozzle for basic research (and many people have been misled).

A careful program was initiated to test the 5th order polynomial contraction and to measure its radiated noise. If the current results are substantiated, it would appear that regular pairing is not an intrinsic phenomenon in jet mixing layers, but rather a consequence of bad choice of facility design or operating conditions. (This would be consistent with the observed disappearance of pairing at high Reynolds number.) Recent measurements at IIT aided by simple analytical correlations have shed some new light on this subject and are discussed in the next section.

#### Recent Measurements

Recent work of Kibens<sup>\*</sup>, in an axisymmetric jet with an acoustically excited shear layer, showed that when the excitation frequency was matched to the preferred frequency of the initial shear layer instability ( $f_e = f_s$ ) and when  $f_s$  was related to the frequency of the jet column instability,  $f_j$ , by

$$f_s = 2^3 f_j$$

then the excitation organized the large scale structures in the shear layer.

<sup>\*</sup>Kibens, V. 1979: "Discrete Noise Spectrum Generated by an Acoustically Excited Jet." AIAA paper No. 79-0592.

In this case the pairing process was fixed at three streamwise locations and subharmonic frequencies produced by this process appeared as discrete peaks in the far field acoustic spectrum. Preliminary measurements in our 2" unexcited, free jet, which has an extremely low disturbance level, indicate that the same coupling mechanism is readily observable in "natural" jets.

If one assumes that the coupling of the two instability modes will occur when  $f_s$  is an integral power of 2 of  $f_j$  so that  $f_s$  can cascade down to  $f_j$  through the pairing process, then

$$f_s = 2^n f_j$$

From inviscid stability analysis one finds that the initial shear-layer instability frequency scales as

$$f_s \propto U^{3/2}$$

This behavior is valid for circular jets with initial shear layer thickness much smaller than their radius and was verified by our experiments. From this, one can show that the jet Reynolds number at which this coupling occurs is given by

$$\widetilde{Re}_D = C_1 [2^n St(U)]^2$$

where  $C_1$  is a constant that depends on the boundary layer thickness at the jet exit;  $n$  is the number of vortex pairings that occur and  $St$  is the jet Strouhal number far downstream (typically between .2 and .5), which in general is a weak function of exit Reynolds number,  $Re_D$ .

Visualization experiments utilizing the smoke wire were conducted using the thin lip jet facility described in Appendix III to determine the effect of the external exit conditions on the jet structure in the initial region. Our preliminary measurements show that when this criterion is met, there is a sharp increase in the amount of energy that is associated with the coherent structures.

Vortex pairing is regular, readily observed and occurs at fixed downstream positions with the number of observed pairings given by  $n$  in the above relation. The constant  $C_1$  was evaluated experimentally in our jet and the following table was constructed from the previous relation.

n	$\tilde{Re}_D \times 10^{-3}$		
	If St = 0.30	If St = 0.37	If St = 0.48
1	0.4	0.6	0.9
2	1.4	2.0	3.7
3	5.6	9.0	15.0 ←
4	22	35 ←	59 ← ?
5	90 ←	140	237
6	360	560	950
7	1440	2250	3800

It was gratifying that additional experiments documented the intensification and organization of the pairing process at the Reynolds numbers indicated by arrows on the table and the number of pairings corresponded to the value  $n$  predicted from the previous relation. Apparently at lower Reynolds numbers  $St$  increases in our facility. This is not in contradiction with earlier investigations.

The main conclusion drawn from the above table and its experimental verification is that the pairing process is often intensified at low Reynolds numbers, while rarely intensified at high ones. This is further influenced by the transition of the shear layer to turbulence prior to its separation from the jet lip, again at high Reynolds numbers. These conclusions may be a key in explaining the observed difference between high and low Reynolds number jets.

New tests on the contraction are currently being completed and a final choice for the common contraction will be made at the meeting of the principals in Holland, Michigan on July 8, 1980. This deferral of a contraction choice

has not delayed the overall experimental program because efforts have been primarily concentrated on preliminary measurements and gaining familiarity with the equipment.

#### A Novel Conditional Measurement Technique

In the course of developing this experiment a new measurement technique has been developed at SUNY/Buffalo which makes wake-free cross-correlations possible and at the same time substantially reduces the computational effort. The technique uses a burst laser Doppler anemometer system (counting mode) in conjunction with multiple hot-wire probes. This novel application of the burst LDA and the unique digital processing techniques have substantially increased the probability for success in the application of Lumley's orthogonal decomposition to determine the coherent structure. The technique is described in detail in Appendix IV.

#### Digital Image Processing of Flow Fields

The combination of a newly developed high-quality smoke visualization technique and digital image processing has been used in recent years at I.I.T. to provide global and local information about several diverse flow fields.

The flow visualization technique utilizes a "smoke-wire" for introducing controlled sheets of smoke streaklines into wind tunnels. The surface of the 0.1 mm diameter wire is coated with uniformly spaced minute droplets of oil which are vaporized by resistive heating. The wire is operated from outside the wind tunnel without interruption of experiments.

The flow visualization images can be produced in real time using an optical digitizer utilizing a vidicon sensor or recorded on negatives to be digitized at a later time. This system permits versatile and immediate operations to be performed on the digitized record of the acquired picture. As an example, several of the unsteady smoke-wire photographic images which are synchronized to the

same instantaneous flow characteristics can be averaged and the resulting "mean" and "fluctuating" images reconstructed. Automatic printing and movie devices are available for advanced graphic output of the processed images.

The overall objectives of the program are to obtain global and local information on simple as well as complex flow processes in a manner which is far less subjective than previously possible through flow visualization. It is possible to objectively extract desired information from an image while suppressing extraneous information which often masks the sought after features. Flowfields analyzed to date include: laminar and turbulent cylinder wakes; grid flows; turbulent jets; unsteady flows past airfoils; turbulent boundary layers; stagnation flows; and wind engineering problems.

## OVERVIEW OF CONTINUING WORK

The work on this program will continue through a contract with IIT which will in turn subcontract to SUNY/B and U.M. The tasks for the next three year period fall into two overlapping categories: first, the completion of the determination of the jet mixing-layer structure and its contribution to the radiated noise; and second, attempts to directly manage and manipulate the coherent structure to understand its controlling mechanism and reduce the radiated noise.

Completion of Coherent Structure Determination - As anticipated in the original proposal, the determination of the coherent structure and its contribution to the radiated noise with the Lumley and Michalke decompositions will take approximately 1 to 1-1/2 years of the new contract period. This is primarily due to the fact that a considerable array of experimental tools had to first be developed. This time schedule is very close to that outlined in the original cooperative proposal.

The modest budget increase granted will allow the continuation of this effort with adequate support (for the first time) and will permit a modest expansion of the scope of the program to cover some existing gaps; in particular, the Mach number effects. Specifically:

- (i) The University of Minnesota will continue its efforts to quantify the variation of the radiated noise with Mach number at fixed Reynolds number. (The initiation of this effort was funded by the supplementary grant received in 8-1-79).
- (ii) The Illinois Institute of Technology will seek to develop visual and quantitative methods to investigate the effects of Mach number on the mixing layer.

- (iii) SUNY/Buffalo will initiate a measurement program using the laser Doppler anemometer to make measurements in jets near Mach 1 from which the coherent structures can be inferred.

The efforts outlined in (ii) and (iii), together with the continuation of that in (i) should complete the picture of our understanding of the subsonic jet and its noise.

#### Changing the Structure and Reducing the Noise

There have been numerous attempts to-date, both to modify the large eddy structure and to reduce the jet noise. To a great extent these have been unsuccessful. Such may be the case here. However, never before will such attempts have been made with information in-hand regarding the details of the jet structure and its effect on the radiated noise. The substantial success achieved over the years by the IIT group in management of ducted flows and recently in wall-bounded shear flows indicates that this team effort is highly qualified in pursuing this avenue again.

Two possible scenarios present themselves. Which is relevant depends on the results of Phase I. If we in fact, find that the large structure does contributed directly to the radiated noise, then the clear goal of this research will be to modify it in such a way as to reduce that contribution without penalizing performance. The detailed information available and the expertise developed in this investigation, as well as the previously developed expertise in turbulence management (IIT), make this a natural project for this team. While success cannot be guaranteed, never will a failure to reduce the noise been made with so much information - this in itself would be significant!

The second scenario presents itself if we should deduce from our data that the coherent structure does not directly affect the radiated noise in practical jets. If the large eddy does not make the noise, then the rest of the turbulence does. Again the goal will be to manage the turbulence in such a way as to reduce



its contribution. Since the large eddy is suspected of dominating the turbulence dynamics it would not be surprising if the best paths toward minimizing the nose also lay in modifying the large structure. Regardless, the capabilities of this team are unrivaled in their ability to evaluate and forecast success for such efforts.

For either of the above scenarios a variety of approaches will be used. These might include nozzle shape changes, shrouds, co-axial jets or quite possibly, a scheme which will arise naturally from the experiments of Phase I. A judicious choice cannot be made until the initial investigation is complete.

Also it will be important to determine the origin and dynamics of the large eddy structure. (The role of the initial investigation was simply to objectively determine its presence and character.) Efforts to elucidate this origin will form an important part of this second phase (especially at IIT and SUNY/Buffalo). Of particular interest will be the acoustically perturbed jet mixing layer (IIT, SUNY/Buffalo). Both of these will be closely linked to concurrent theoretical efforts.

## List of Personnel Associated with Program

### SUNY/Buffalo

Dr. W. K. George, Professor of Mechanical and Aerospace Engineering  
 S. P. Capp, Research Associate  
 Dr. P. Buchhave, Visiting Scientist  
 S. Khwaja, Graduate Assistant  
 N. Nee, Graduate Assistant  
 R. Suhoke, Jr. Technician  
 K. Yamamoto, Research Associate

### IIT

Dr. H. M. Nagib, Professor of Mechanics, Mechanical & Aerospace Engineering  
 Dr. J. L. Way, Co-Principal Investigator  
 Dr. R. A. Wigeland, Co-Principal Investigator  
 Dr. T. Tan-atichat, Post Doctoral Fellow  
 R. E. Drubka, Research Assistant  
 T. C. Corke, Research Assistant  
 Y. Guezennec, Research Assistant

### University of Minnesota

Dr. R. E. A. Arndt, Professor of Civil Engineering  
 Dr. J. Killen, Research Associate  
 B. McDonald, Graduate Assistant  
 D. Long, Graduate Assistant

## Honors, Promotions, Degrees Awarded, etc.

### SUNY/Buffalo

W. K. George, Jr. - Promoted to Full Professor  
 S. P. Capp - Promoted to Research Associate  
 P. Buchhave - Ph.D. (1979)

### IIT

H. M. Nagib - Promoted to Full Professor  
 R. A. Wigeland - Appointed to Assistant Professor  
 J. Tan-atichat - Ph.D. (1979)  
 R. Drubka - Recieved IIT Fellowship for Outstanding Scholarship.

List of Publications and Reports (cont.)

Buchhave, P. and George, W.K. "Measurement of Turbulence with Burst Processor Laser Doppler Anemometers", Bull. of the American Physical Society, Series II 23, 8, p. 995. 1979

Buchhave, P., George, W.K. and Lumley, J.L. "The Measurement of Turbulence with the Laser Doppler Anemometer", Annual Rev. Fluid Mechanics, 11, 443-503, 1979. (Distributed as TRL Report No. 101).

Corke, T. and Y. Guezennet, "Phase Conditioned Visualization of the Near Wake of a Circular Cylinder Using the Smoke Wire Technique", Bull. of American Physical Society, p. 995, Nov. 1978.

George, W.K. "Processing of Random Signals" in Dynamic Measurements in Unsteady Flow (Proc. of the Dynamic Flow Conference 1978, Kovasny et al. editors) pp. 557-800, 1979. (Distributed as TRL Report No. 105).

George, W.K. and Beuther, P.D., "Interpretation of Turbulence Measurements in High Intensity Turbulent Shear Flows", Bull. of the Amer. Phys. Soc., Series II 24, 8, 1979.

George, W.K., Beuther, P.D. and Arndt, R.E.A., "Pressure Spectra in Turbulent Free Shear Flows", presented at AIAA Aeroacoustic Meeting, E. Hartford, Conn. June 4-6, 1980 and to be submitted to the AIAA Journal. (To be distributed as TRL Report No. 104.)

George, W.K. and P. Buchhave, "Measurement of Unsteady Flow with Burst Processor Laser Doppler Anemometers", Proceedings of the 15th Annual Meeting of the Society of Engineering Science, 1978.

George, W.K. and P. Buchhave, "Measurement of Turbulence with Burst Processor Laser Doppler Anemometers", Bull. Am. Phys. Soc., Series II, 23, 8, p. 995, 1978.

Nagib, H., Guezennet, Y. and Corke, T., "Application of a Smoke Wire Visualization Technique to Turbulent Boundary Layers", Proceedings of Workshop on Coherent Structure of Turbulent Boundary Layers, Bethlehem, Pa. 1978.

Nagib, H., Cooke, T., Helland, K. and Way, J. "Computer Analysis of Flow Visualization Records Obtained by Smoke Wire Techniques" in Dynamic Measurements in Unsteady Flow (Proc. of the Dynamic Flow Conference 1978, Kovasny et al. eds.), pp. 567-582, 1979.

Nagib, H.M. and Tan-atichat, J., "Effect of Contraction of Turbulence", Bull. Am. Phys. Soc., Series II, 24, 8, 1979.

Tan-atichat, J., Nagib, H., and Drupka, R. "Effects of Axisymmetric Contractions on Turbulence of Various Scales". IIT Fluids and Heat Transfer, Report No. R-80-1, 1980.

Wlezieu, S., and Drupka, R. "Hot Wire Linearization and Angularity Corrections", Bull. Am. Phys. Soc., Series II, 8, 1979.

Yamamoto, K. and Arndt, R.E.A., "Peak Strouhal Frequency of Subsonic Jet Noise as a Function of Reynolds Number", AIAA Paper 79-1525, 1979.

Yamamoto, K. and Arndt, R.E.A. "Low Reynolds Number Jet Noise", to be submitted to AIAA Journal in 1980.

Yamamoto, K. Introduction to Aeroacoustics (Japanese) to be published in 1981

Yamamoto, K. "Acoustic Field Generated by Subsonic Jets at Low Reynolds Numbers", J. Acous. Am., 64, 1978.

Advisory Committee - (1978-1980)

Lt. Col. Lowell Ormond,  
Chairman  
Air Force Office of  
Scientific Research

Dr. Marvin Goldstein  
NASA/Lewis

Prof. Frank Champagne  
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Prof. Mark Morkovin  
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Prof. John Lumley  
Cornell Univ.

Prof. John Ffowcs-Williams  
Cambridge Univ.

Prof. David Crighten  
Leeds Univ.

Dr. Valdis Kibens  
(McDonald-Douglas  
Research Labs.)

List of Publications and Reports Resulting in Whole or in Part from This Work

Arndt, R.E.A. and W.K. George. "Pressure Field and Cavitation in Turbulent Shear Flows". Proceedings 12th Symposium on Naval Hydrodynamics, National Academy of Science, June 5-9, 1978.

Arndt, R.E.A. "A Sketch of Aeroacoustics". The Shock and Vibration Digest, V. 10, #12, Dec. 1978.

Arndt, R.E.A. and Yamamoto, K., "Asymmetry of a Circular Jet Observed in Near and Far Fields", AIAA Journal, April 1979.

Arndt, R.E.A., Holl, J.W., Bohn, J.C., and Bechtel, W.T., "The Influence of Surface Irregularities on Cavitation Performance", J. of Ship Research, Sept. 1979.

Arndt, R.E.A., "Recent Advances in Cavitation Research", Advances in Hydro-Science, V.T. Chow, ed. (to appear)

Arndt, R.E.A., "Cavitation in Fluid Machinery and Hydraulic Engineering", Annual Review of Fluid Mechanics, M. Van Dyke and J.V. Wehausen, co-editors, (to appear January 1981).

Arndt, R.E.A., "Influence of Polymer Additives on Cavitation in Jets", Cavitation and Polyphase Flow Forum, ASME, New York, 1980

Buchhave, P. "The Measurement of Turbulence with the Burst-Type Laser Doppler Anemometer - Errors and Correction Methods". Ph.D. Dissertation, Department of Mechanical Engineering, State University of New York at Buffalo, July 1979. (Distributed as TRL Report No. 106.)

Buchhave, P. and W.K. George. "Errors and Correction Methods in Turbulence Measurements with an LDA", Proceedings of LDV-III Laser Velocimetry in Hostile Environments, Purdue Univ. Workshop, July 11-13, 1978. (Distributed as TRL Report No. 107).

APPENDIX IDescription of SUNY/Buffalo Experimental Facilities

Over the past two years two open jet facilities have been developed - a large 8" diameter jet and a smaller 3" diameter jet. The large jet is driven by a 45 HP electric blower through a standard diffuser and settling chamber, and is capable of exit speeds in excess of 150 ft/sec. (Jet Reynolds Number: 700,000). The small jet can be driven either by a small blower or compressed air and has a maximum exit speed of 60 ft/sec. (Jet Reynolds Number: 100,000). The two facilities have overlapping operational ranges. Turbulence intensities as low as 0.1%, have been observed in the small jet when using compressed air. Both facilities have a background turbulence level of about 0.35% when operated conventionally.

Several data acquisition systems have been developed for use in different aspects of the jet experiments. A PDP 11/34 minicomputer is the central facility and can be accessed by either a 200 kHz, 15 bit, A/D converter, or by a special transient recorder capable of handling 8 channels of signals at frequencies up to 2MHz/channel. Data can be stored on magnetic tape or disk, or transferred via serial data line to the University Cyber for further processing.

A LSI-11 based microcomputer system (Heathkit H-11) is dedicated to the processing of the Laser Doppler Anemometer signals generated by the DISA 55X two color system. The H-11 is interfaced to the PDP 11/34 to allow simultaneous processing of hot wire and LDA signals.

In addition to the two color Argon Ion Laser Doppler Anemometer system, a smaller He-Ne system is available for simultaneous use and for flow diagnostics. The combination of these systems with eleven channels of hot wire anemometry provide an adequate equipment base for the proposed and ongoing experiments.

A modern five degree of freedom traversing system is complete and operational. It is operated under microprocessor control, and can either be used independently, or under control of the PDP 11/34 or H-11.

## APPENDIX II

## AEROACOUSTIC TEST FACILITY

The anechoic test facility at the University of Minnesota was designed specifically for investigation of jet noise. The facility consists of an anechoic chamber with a porous wall at one end, a treated collector at the other end, an air recirculation system, hot wire and microphone traversing systems, and a mini-computer based data acquisition system.

Aerodynamics

Figure 1 illustrates the overall set-ups. Particular attention has been given to the proper modelling of entrainment flow. As shown in the sketch, flow entrained by the jet mixes with the primary jet flow and passes into an acoustically treated shroud. The combined flow from the jet and its entrainment is recirculated by a blower through a treated duct.

The air supply for the jet is piped in from a compressor located in the basement of the Laboratory. A filter and water trap is used to remove impurities. Three different flow regulation circuits are available, each tailored to a different range of flow rate. The maximum controllable flow rate is 35 liters/sec at standard conditions, which corresponds to a Mach number of 0.8 in a 13 mm nozzle (the maximum size envisioned for the test program).

Details of the air supply system are shown in Fig. 2. A flexible connection between the flow control valves and the inlet to the heater eliminates unwanted vibration associated with the compression and regulation of the shop air. The heating element has the capability of heating the jet flow to temperatures in excess of that necessary for the jet to be at room temperature at Mach 2 and maximum flow rate. This insures isothermal operation over the planned Mach number range of 0.25 to 0.9. A system of perforated plates, honeycomb and screens is used for turbulence management. A small muffler (not shown) is inserted between the flexible connection and the heating element for attenuation of high

frequency noise from the pressure regulators. The rest of the flow noise in the supply system is attenuated with a specially designed muffler inserted between the heater and the turbulence management system.

The inside diameter of the settling chamber is sufficiently large to provide for contraction ratios in excess of 100, with the largest anticipated nozzle (25 mm).

Two contractions are used as shown in Fig. 3. The first is common to all the nozzles to be used in the test program. Its shape is based on a fifth order polynomial which has excellent aerodynamic characteristics. A series of nozzles, ranging in size from 1.3 mm to 12 mm are fitted on the end of this contraction. The contraction ratio for each of these nozzles is well in excess of the limiting value of 10, above which the aerodynamic characteristics are independent of this parameter. The shape of each nozzle (e.g. matched cubic or fifth order polynomial) will be identical for each nozzle. At present, four different nozzle designs, all 7 mm in diameter, are being evaluated. When a decision is reached on the design that will be common to the rest of the test program, additional nozzles will be fabricated in different sizes.

The measured nozzle turbulence level at the exit plane of a 6 mm diameter nozzle is less than the noise level of the hot wire instrumentation at 30 m/sec (less than 0.3 percent).

#### Acoustical Characteristics

The anechoic chamber is cubical in shape, with inside dimensions of 230 cm on each side. The acoustical treatment is Urethane foam designed for a low frequency cutoff of 1000 Hz.

Special tests were made to determine the acoustic properties of the foam at very high frequencies (Ref. 1). The absorption characteristics are excellent over the frequency range of interest.

The background noise, high-passed at 1000 Hz, is of the order of 50 dB or less. There is no change in the measured background level with the blower on or off. The spectral level ( $p^2/\text{Hz}$ ) is less than 20 dB over the entire frequency range of interest.



### Data Acquisition and Instrumentation

Microphones and hot wire probes can be positioned at predetermined positions in the test chamber. Three different traversing mechanisms are used, allowing positioning in terms of spherical, cylindrical, or axisymmetric coordinate systems. One unit is manual, used for positioning a reference microphone. Its positioning accuracy is 0.004"/foot with a resolution of 0.001". Its angular travel is a full 360° with an accuracy of 1 min/360° and a resolution of 15 sec. A second traverser is automated with digital and analog position readout. Its accuracy is the same as the manual unit. The stepping motor is capable of giving a resolution of 4000 steps/in. in linear travel and 100 steps/degree in angular travel. A third traversing system is used for positioning instrumentation azimuthally around the centerline of the jet. The automated equipment is designed to be driven by computer.

B and K microphones and amplifiers are used for sensing sound. Two channels of TSI hot wire anemometry are available for turbulence measurements. TSI sub-miniature probes are the primary sensors for turbulence research.

The data acquisition and analysis system is based on a PDP11-34 computer with an RSX operating system, as shown in Fig. 4. A Preston model GMAD-1 A/D converter is used with a maximum sampling rate on two channels of 255 kHz. This allows frequency analysis to approximately 100 kHz. Output can be printed using a Dec Writer LA-36 or displayed with a Tektronix 4010 Graphic Display Terminal. Hard copy can be made on a Tektronix 3662 X - Y Digital Plotter.

A software package is being developed to provide the following data analysis functions:

- 1) Single or dual channel FFT (power spectrum)
- 2) Cross spectrum analysis
- 3) Inverse transform
- 4) Autocorrelation
- 5) Crosscorrelation
- 6) Convolution
- 7) Transfer function analysis
- 8) Coherent output power

- 9) Signal averaging
- 10) Probability density histogram

### Test Matrix

Several criteria were used in establishing nozzle sizes. It was necessary to have the capability of testing either at constant Reynolds number over a range of Mach number or vice versa. In addition there are limitations on the sensitivity and frequency response of the various B&K microphones (1/8", 1/4" and 1/2" being available for this study). There is a low frequency cut-off of the chamber (1000 Hz) and a maximum controllable flow rate of 35 liters/sec. These limitations are reflected in plot of Mach number vs jet diameter as shown in Fig. 5. The lower limits on sensitivity of each microphone result in a lower limit in Mach number, assuming that the microphone is positioned at 100 diameters from the jet. It was also desired that tests could be carried out over a Helmholtz number range of 0.06 to 0.24 where Helmholtz number is defined as

$$He = \frac{fd}{a_o}$$

d = jet diameter

f = frequency

a<sub>o</sub> = speed of sound

The high frequency limit of the microphone defines the minimum jet size at all values of Mach number, whereas the 1000 Hz cutoff frequency defines the maximum jet size at low Mach number and maximum controllable flow rate limits the maximum jet size at higher Mach numbers. The test matrix shown, based on five nozzles, allows a reasonable range of Mach number and Reynolds number.

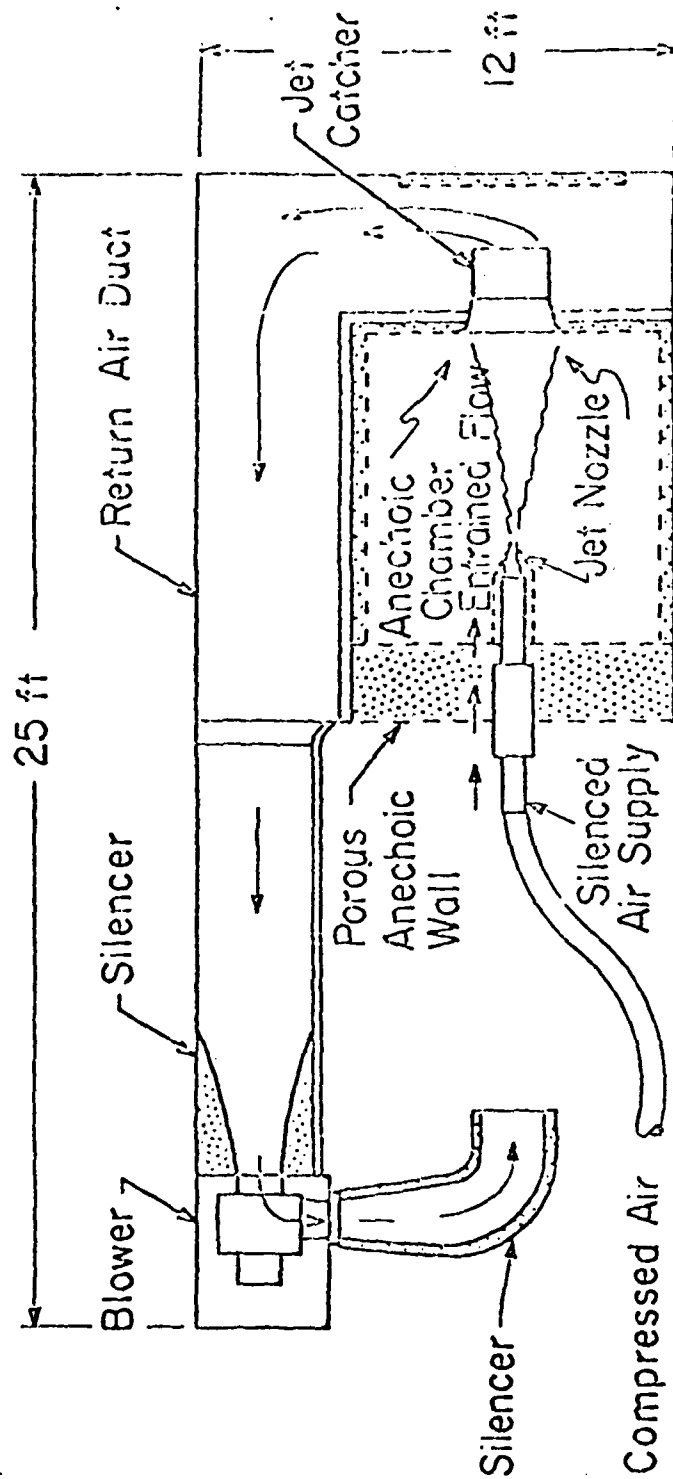


Fig. 1 - Aero-acoustic Test Facility.

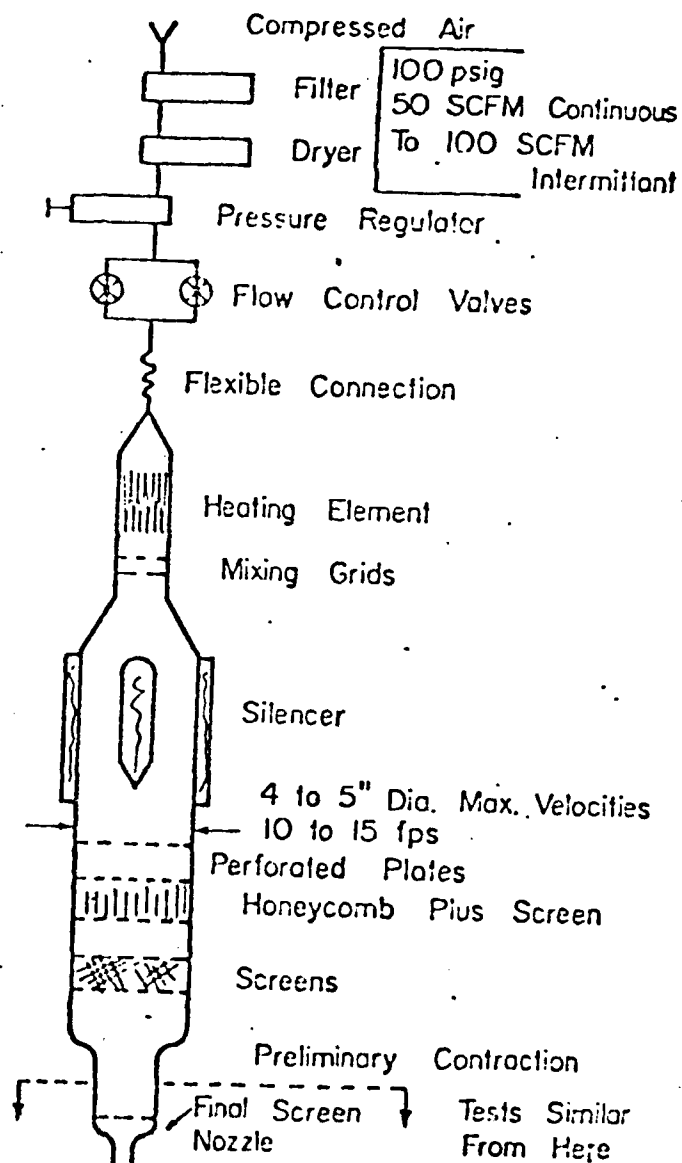


Fig. 2

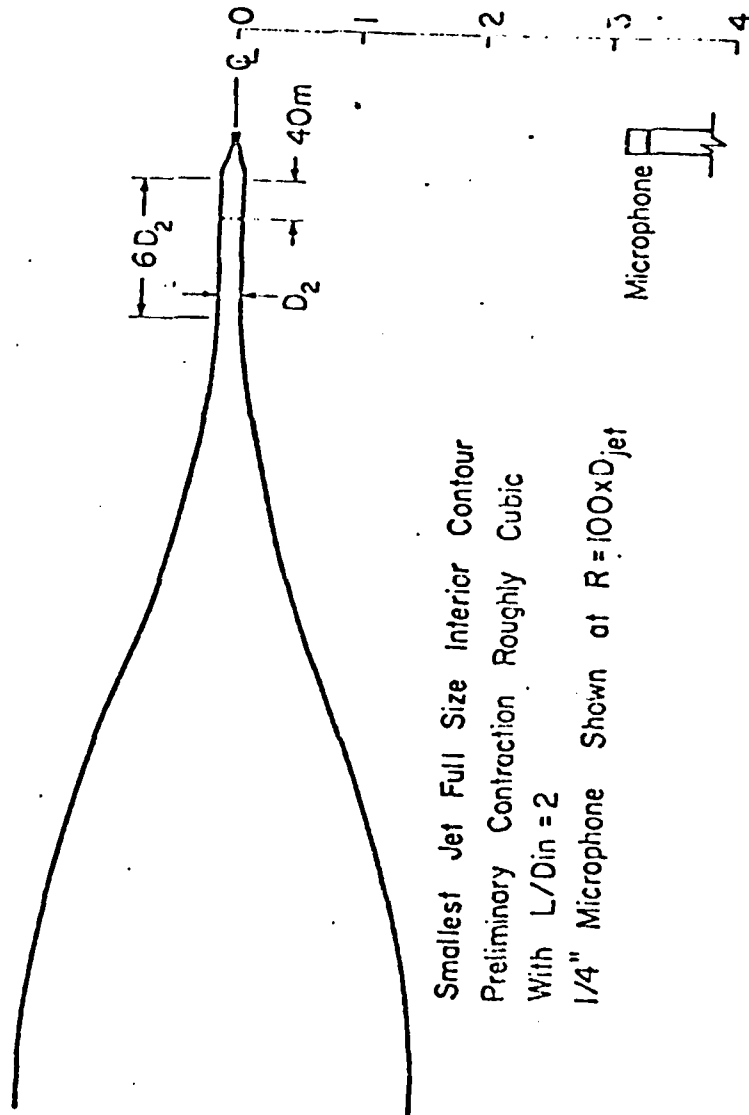


Fig. 3

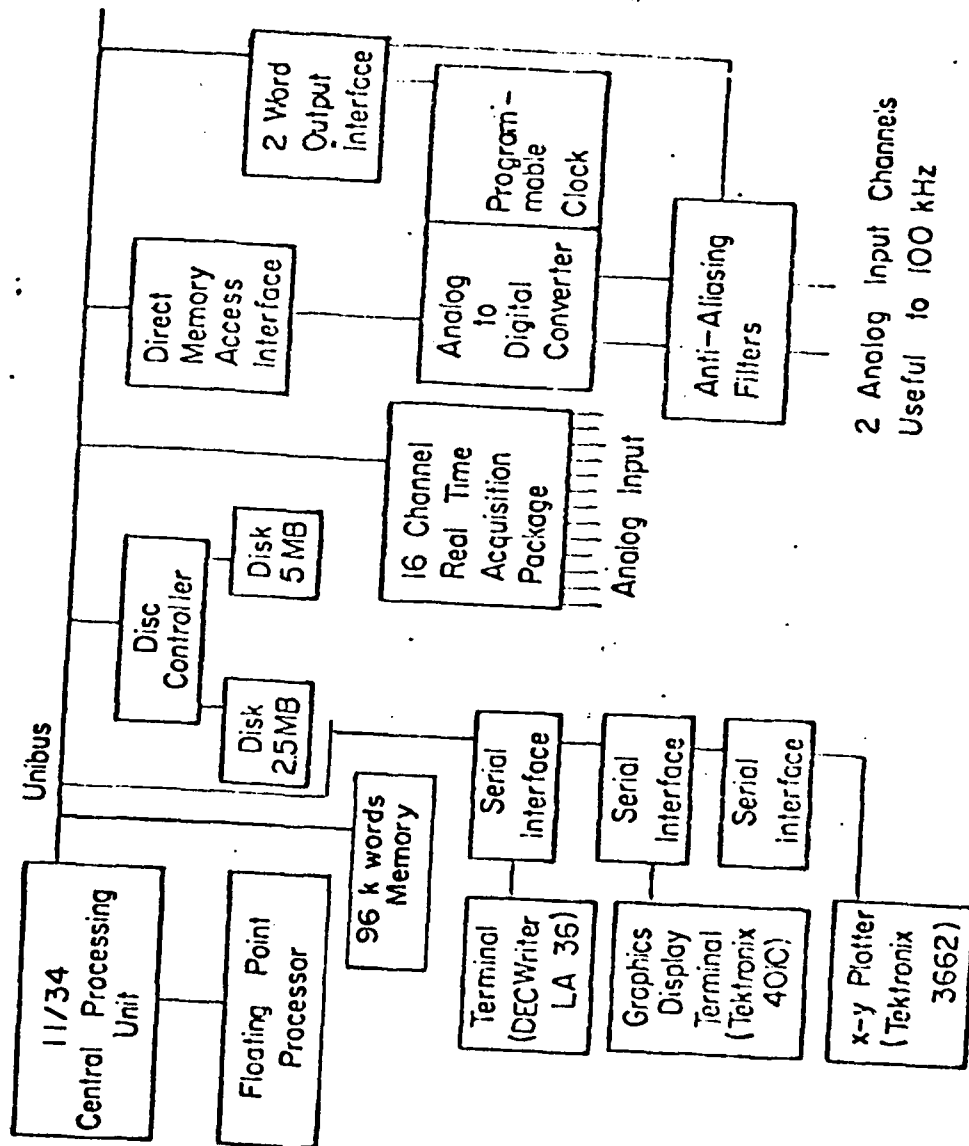


Fig. 4

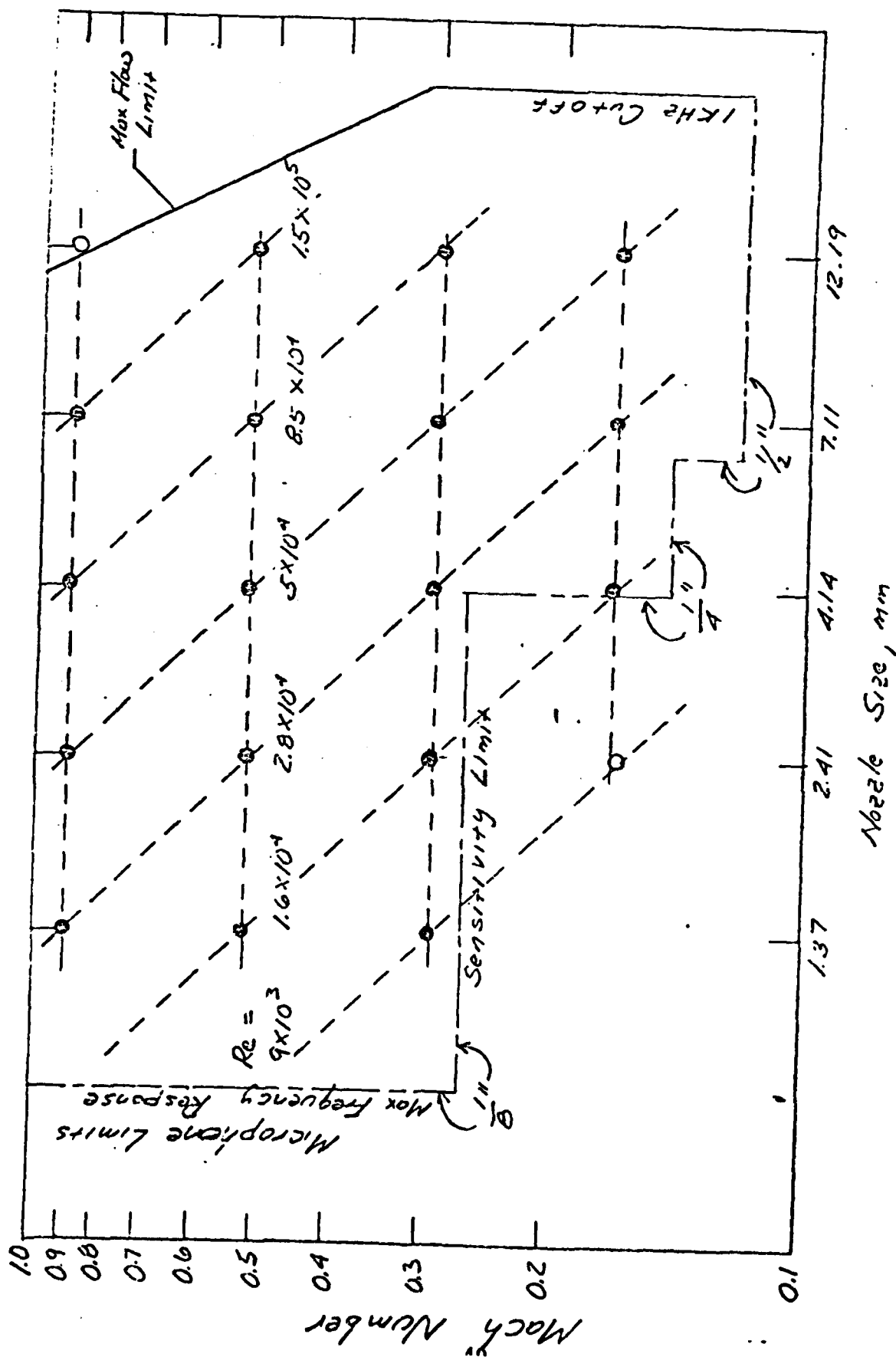


Fig. 5 - Test Matrix.

APPENDIX IIIExperimental Facilities at IIT

During the course of this study, three free jet facilities are being utilized. In the first of these, compressed air enters a large acoustically lined and baffled plenum chamber which is fitted with suitable turbulent management devices. In its normal configuration, air exits the chamber via a 6" diameter duct (3" in length) and enters a suitable contraction. Various contractions have been carefully manufactured from plexiglass with area ratios of 2, 4, 9, 16, 23.5 and 36. In each of these cases, the length of the contraction is equal to the inlet diameter ( $L/D = 1$ ). In addition, contractions having  $L/D$ 's of 0.25, 0.5 and 1.5, with an area ratio of 9, were also constructed. For all of the above contractions, the contour is described by two matched cubic equations. Another contraction was fabricated using a single fifth-order polynomial contour with an area ratio of 9 and an  $L/D = 1$ .

Using a contraction with an area ratio of 9 and an  $L/D = 1$ , exit turbulence intensities were measured to be as low as 0.05%. The maximum achievable Reynolds number using this configuration and contractions is 200,000. When higher velocities are required, the facility can be supplied using a 50 hp blower to raise the maximum Reynolds number to nearly 1,000,000.

This facility also has the advantage of permitting the thickening of the boundary layer at the jet exit by one of two methods. In the first, ducts of various length can be inserted prior to the contraction, thereby, changing the inlet boundary layer. The second method consists of thickening the exit boundary layer with the aid of extension tubes connected to the jet exit in a manner similar to that used by Kibens\*. In this way we are able

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\* Kibens, V. 1979, "Interaction of Vortex Pairing with Jet Pipe Resonance", presented at the 32nd meeting of the American Physical Society, Division of Fluid Dynamics, paper AB3.



to control the momentum thickness of the boundary layer at the jet exit.

The second of these facilities was utilized to examine the effect of the nozzle lip size or jet-exit plane configuration on the developing-jet structure. In this facility, compressed air passes through a diffuser and various turbulence manipulators before exiting from a thin lip 1"-diameter nozzle. Various attachments can be placed on the nozzle to change its exit lip size or external conditions. Besides the initial thin lip nozzle a lip thickness of 0.5" and an 18" diameter exit plane were examined.

The third jet facility, presently under construction, will include many of the flexible features of the first facility described but on a larger scale. The jet will exit from a 4" diameter nozzle having a contraction ratio of 9 and length to inlet diameter ratio of 1. The contour for the nozzle shape will be identical to those at the University of Minnesota and at the State University of New York at Buffalo and will thus provide a benchmark for a comparison of the results between the 3 universities.

The recently developed image processing techniques in conjunction with the IIT Data Acquisition and Processing System (DAPS) have been further upgraded by the addition of new hardware and inhouse developed software to allow for real time digital image processing. Flow visualization records can either be obtained by traditional photographic methods and then digitized, or directly by the newly obtained Optical Digitizer equipped with a vidicon sensor. These records can then be stored on disk or magnetic tape to be processed either on the DAPS using the newly acquired array processor or on a Univac 1110 using the sophisticated software packages developed over the last year at IIT.

Traditional turbulence measurements will be obtained using single and x-wire probes. A motorized mechanism can traverse the probes and provide

a probe-position signal to the data acquisition system. Analog signal processing techniques will be used for the diagnostics of the flow while the digital acquisition system will be utilized for the final measurements, providing a permanent record of the results.

APPENDIX IVMixed Mode LDA/Hot Wire Processing

The breakthrough with the LDA at SUNY/Buffalo has made possible a significant change in the manner in which the experimental program is to be carried out. The mixed mode hot-wire laser Doppler method which has been adopted eliminated two of the anticipated major obstacles to the success of this experiment namely, the problem of probe-wake interference and the problem of the enormous quantity of data. The details of how this has been accomplished are included below.

This effort was initiated approximately 1-1/2 years ago in an attempt to use the laser Doppler anemometer to validate the hot-wire calibration schemes being used in the jet program. The outcome has been not only a complete understanding of the so-called burst realization LDA but the development of a mixed mode LDA/hot-wire scheme which combines the advantages of both techniques (non-intrusive and moderate cost) with a new signal processing technique which eliminates the two major problems of digital handling of random data (statistical convergence and aliasing).

The contribution to understanding the "burst realization" LDA have been described in detail in the publications cited under this program. In brief, it is shown by theory and experiment that algorithms can be generated which use the individually arriving particles in an LDA scattering volume to construct the entire time history statistics of the flow field - even though there is no signal most of the time! Concurrent with the theoretical development has been the development of a sophisticated computer interface by DISA designed specifically for a modified burst processor which allows implementation of the algorithm.

While the burst processor mode described above has many advantages - alias-free, bias-free, non-intrusive - it suffers from the primary disadvantage of all LDA systems - it is expensive. This is particularly important when

multiple point statistical measurements are anticipated. The hot-wire on the other hand, although relatively inexpensive, has a number of disadvantages, the most important in this context being its intrusive nature and the fact that since it generates a continuous signal it must be sampled at high rates to avoid aliasing. A consequence of the latter is that large amounts of "unnecessary data" are generated which must be analyzed. By operating in a mixed mode with the burst processor LDA upstream and hot-wire downstream, not only can expense be minimized and the familiar leading probe-wake problem be eliminated, but a tremendous savings in data-processing cost and complexity can be effected.

The technique will be briefly described here: The hot-wire output is continuously monitored at a slow rate by an A/D converter with a buffer memory. When a scattering particle enters the measuring volume of the upstream LDA, its velocity is measured and a command is generated to freeze the hot-wire data in memory. All cross products between the time-sampled hot-wire data and the single LDA realization are computed and an instantaneous realization of the space-time correlation is generated for all time delays. The process is repeated until convergence is achieved. Time for convergence is determined by the usual criteria for measurement of random processes. By avoiding the necessity to rapidly sample the data and carry out the usual cross-product (or Fast Fourier transforming), a substantial reduction in data processing is achieved. In the jet experiment funded by this grant the savings is about  $10^5$  in quantity of data and means that all processing can be effected in a minicomputer instead of a large central facility.